



Short communication

Empirical evaluation of the improvement of battery output when coupled with a capacitor bank



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HIGHLIGHTS

- We measured the potential and current from a battery with and without capacitors.
- We estimated the internal resistance of the battery and the total energy delivered.
- The capacitors increased the retrievable power for three types of batteries used.
- The capacitor bank also increased the life of the charge.

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ABSTRACT

It has been demonstrated experimentally that a capacitor bank when connected in parallel with a battery increases the energy output by mitigating the effects of high current spikes in the load. High current draws are taken from the capacitor bank which can furnish a small amount of energy quickly. The battery which can furnish substantial energy over a period of time then recharges the capacitor bank during times of decreased load. With a current square wave ($P-P$ of 1.5 to $2\times$ the average), capacitors afforded an increase in the retrievable energy of approximately 8% for a lead acid battery, 40% for a rechargeable lithium ion battery, and 46% for a non-rechargeable lithium ion battery.

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1. Introduction

The move toward mobile power sources has placed ever more severe requirements on batteries, and necessitates every possible performance improvement that can be made. One strategy that is taken as axiomatic is placing a super capacitor (or bank of super capacitors) in parallel with the battery, for example references [1–3]. In so doing, any sudden demand for power is met by the capacitor bank, thereby minimizing power loss through the internal resistance of the battery. To illustrate the effect, consider the Thevenin representation of a battery; a constant voltage supply, V_{Th} , in series with a resistor, R_{int} , the internal resistance of the

battery. Factors contributing to R_{int} include diffusion/transport of ions and electrode kinetics. When loaded, the usable power is decreased by $I^2 R_{int}$. Suppose that the load current fluctuates about a constant value, I_0 , such that $I = I_0 + f(t)$. The average power loss is $\langle [I_0 + f(t)]^2 \rangle R_{int}$, which reduces to $I_0^2 R_{int} + \langle f(t)^2 \rangle R_{int}$. The cross term $\langle I_0 f(t) \rangle$ vanishes because $\langle f(t) \rangle = 0$ by hypothesis.

There is no way to decrease the $I_0^2 R_{int}$ power loss, since this is a constant, and the battery must supply an average current of I_0 . However, reducing the $\langle f(t)^2 \rangle R_{int}$ term is possible through the use of a capacitor. The capacitor only manages power fluctuation and need not supply any net current over time. Although this analysis is overly simplistic, it suffices to show how a capacitor could improve battery performance. A more detailed analysis of the battery/capacitor system which also accounts for the internal resistance of the capacitor bank is given elsewhere [4]. For our purposes it suffices to express the retrievable power from the battery as, $P = VI_0 - I_0^2 R_{int} - \Delta I^2 R_{int}$, where V is the nominal battery voltage, I_0

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is the average or steady state current, and ΔI is the peak amplitude of the current swing. Estimates of the retrievable battery power with and without the capacitor bank may be made with the follow pairs of equations.

$$\text{Battery Power without Capacitor} = VI_0 - I_0^2 R_{\text{int}} - \Delta I^2 R_{\text{int}}$$

$$\text{Battery Power with Capacitor} = VI_0 - I_0^2 R_{\text{int}}$$

There are three implicit assumptions in this relationship: (1) square wave load, (2) ideal capacitors with negligible internal resistance, and (3) short square wave period relative to the $R_{\text{int}}C$ time constant. Therefore, these equations represent an idealized model.

Several papers modeling the capacitor/battery combination in high power applications have been published [e.g. [4–8], and Jia et al. has demonstrated the use of super capacitors for power smoothing [9] both theoretically and experimentally. Recently, Hochgraf et al. [10] published results of a long term study of the effect of super capacitors on the degradation of lithium ion batteries under load with current spikes. Based on their modeling and experimental results, the authors concluded that the super capacitors substantially retarded the cyclic degradation of the battery. The goal of this investigation is to quantify the improvement in battery performance when used in combination with a capacitor bank.

2. Experimental

Consumer grade batteries were selected for these evaluations. The lead acid battery was a 12 V Interstate SP-30, the non-rechargeable lithium ion batteries were 3 V 1300 mAh Tenergy 123 A, the rechargeable lithium ion battery was a 3.6 V 1000 mAh Ultrafire LC 16340, and the super capacitors were 2.7 V 400 F Tecate Powerburst. A schematic of the test apparatus is given in Fig. 1. The capacitor bank was constructed to match the operating potential of the battery. For experiments involving the lead acid battery, the bank consisted of six capacitors connected in series (total capacitance of 66.7 F), and for the experiments involving the lithium ion batteries, the bank consisted of two capacitors connected in series (total capacitance of 200 F).

The voltages of the system and each capacitor as well as the battery and capacitor currents were monitored throughout each discharge experiment. Voltages of the individual capacitors were not particularly relevant in this study, however, they were logged for diagnostic purposes in case one of the capacitors failed. Current drawn from the battery and capacitor bank was taken as $1000\times$ the voltage drop across the $1\text{ m}\Omega$ shunt resistors, positive being current out, and negative being current in. Because these resistors are so

small, they introduce negligible error in the evaluation. Data was logged at 1 s intervals with an Agilent 94970A data acquisition system. The acquisition interval was confirmed by the time stamp of each reading. An electronic load controller was used to draw current from the system. It was either a 3H Industries Swinger II SW2-300 (lead acid battery experiments), or Hewlett Packard 6063A (lithium ion experiments). Symmetric square wave loads were used in these experiments; for the lead acid battery, 15 s at 40 A and 15 s at 10 A, and for the lithium ion batteries, 5 s at 4 A, and off for 5 s.

The batteries were fully charged prior to each run (13.8 V for the lead acid, and 4.2 V for the rechargeable lithium ion). Charging of the lead acid battery was done with a Tektronix P52520G programmable power supply set to 13.8 V and current limited at 1 A. Voltage was applied to the battery until the set voltage was attained, and the current was no more than 20 mA. The battery was allowed to sit for at least 1/2 hour prior to running the discharge experiments. Charging of the lithium ion battery was done with the charger furnished by the manufacturer. The non-rechargeable lithium ion batteries were used as purchased, then discarded after each run. In experiments where capacitors were part of the power system, the capacitor bank was charged to match the open terminal voltage of the battery. Charging of the capacitors was also done with the Tektronix programmable power supply. Because this pre-charging introduces an additional amount of energy, $1/2 CV^2$, into the system, only the current from the battery was used to evaluate the retrievable energy; the energy from the capacitor was removed from the calculations.

The internal resistance of the typical capacitor used in this set of experiments was evaluated with the current jump method [11]. An approximate value of $7\text{ m}\Omega$ was obtained, which is consistent with the manufacturer's specified limit of $12\text{ m}\Omega$.

3. Data analysis

Evaluation of the battery performance requires measurement of the open terminal voltage of the battery, the internal resistance of the battery, and current and power from the battery and capacitor bank. The current from the capacitor and battery were measured directly ($1000\times$ voltage drop across the shunt resistors). The power from the battery and capacitors were calculated from the product of the system voltage and the respective currents. Energy was calculated by performing a running summation of the power (note: the 1 s sample time makes the conversion of power to energy a direct summation). The energy loss by the cyclic charge and discharge of the capacitor bank was calculated by summing the square of the capacitor current times the internal resistance of the capacitor bank over the entire run.

The open terminal voltage and the internal resistance of the battery were obtained from a load line-type of analysis of the high and low current states of the load profile, according to the equation, $V_{\text{sys}} = V_{\text{Th}} - I_b R_{\text{int}}$. Since V_{sys} and I_b were measured, the two current states of the load cycle allowed calculation of the Thevenin parameters, V_{Th} (the open terminal voltage) and R_{int} . In order to weight each data point equally, a least squares estimate of the Thevenin equivalent values was made from an entire load cycle (30 points for the lead acid system and 10 points for the lithium ion systems). The least squares analysis was allowed to “roll” over time by incrementing the set of data points used in each analysis by one. Hence temporal dependences of the open terminal voltage and the internal resistance were obtained.

For each experiment, the realized energy improvement was compared to the expected value. This expected improvement was calculated using the nominal open terminal voltage of battery for V , the average current load for I_0 , $1/2$ the peak to peak amplitude of the current for ΔI , and the experimental estimate for R_{int} . The calculated power output corresponds to the slope of a plot of

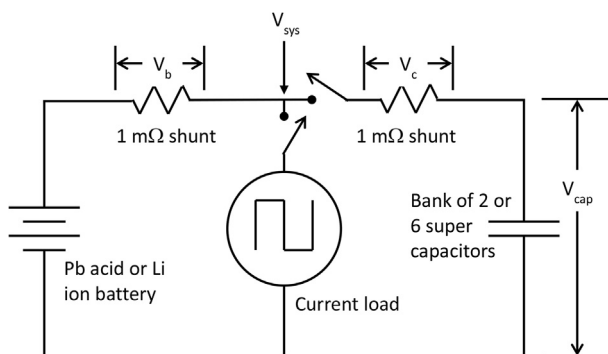


Fig. 1. Schematic of the experimental setup.

energy versus time in the linear (or near linear) portion of the curve. As the battery nears depletion, the energy-time curve flattens, and becomes constant. The point at which this occurs depends on the efficiency the electrode reactions throughout the discharge. This latter effect is beyond the scope of the simple model, and gives an additional source of improvement by the capacitor bank.

4. Results and discussion

Power partitioning for a portion of discharge of the lead acid battery/ultracapacitor system is given in Fig. 2. Characteristic partitioning curves such as these have been predicted by Dougal et al. [4], save that their treatment dealt with pulses rather than symmetric square waves. Note that the power delivered by the capacitor bank was well centered about zero, indicating that little if any net energy was gained from discharge of the capacitors. Also note that the power demand on the battery reached the full load requirement near the end of the cycle (nominally 480 Watts for the high load state and 120 Watts for the low load state). Because the battery carries most of the load during the current spikes, only a modest improvement at best is expected.

Fig. 3A shows the internal resistance of the lead acid battery during discharge with and without the capacitors. As expected, the internal resistance remained relatively flat at approximately 30 mΩ toward the depletion point, then increased substantially. Since the estimated value of the internal resistance was $30\times$ that of the shunt resistor, it is clear that the resistor had a minimal effect on the results. Interestingly, the battery depletion point occurred later in the discharge when the capacitors were present. Fig. 3B shows the energy extraction curve for two cases. Note that in the linear portion of plot, the curves are practically superimposed. This indicates that the capacitors have only a small effect in the early stages of discharge, which is consistent with the energy partitioning curves in Fig. 2. In fact, calculation of the power loss terms, as given in the introduction show that the steady state power ($V I_0 - R_{int} I_0^2$) is 281 Watts, and the total power including the fluctuation loss ($R_{int} \Delta I^2$) is 275 Watts. The increase from 275 Watts to 281 Watts is an improvement of only 2%. Such a subtle difference in slope would not be evident from the energy retrieval curves. However, late in the discharge, the system without capacitors shows a noticeable decrease from the ideal, linear line. Notice that this happens about 1500 s into the run; the same time at which R_{int} increases rapidly. Throughout the course of the two runs, a total of 502 kJ was delivered by the battery in the “without capacitor” configuration and 541 kJ was delivered in the “with capacitor” configuration, an improvement of 8%. Clearly the battery has retained charge longer with the capacitors present. This effect

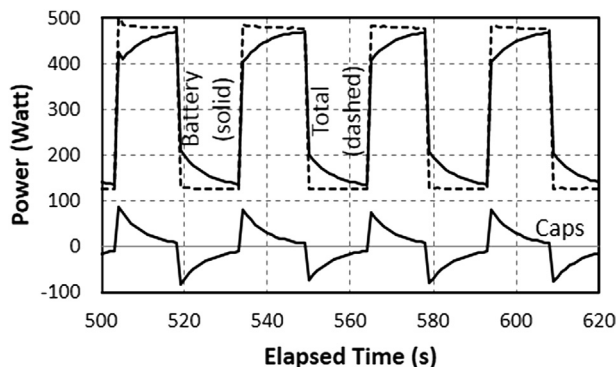


Fig. 2. Power partitioning of the lead acid battery/ultracapacitor system during load cycling, showing the contribution from the battery and capacitors, and the total power (dashed line).

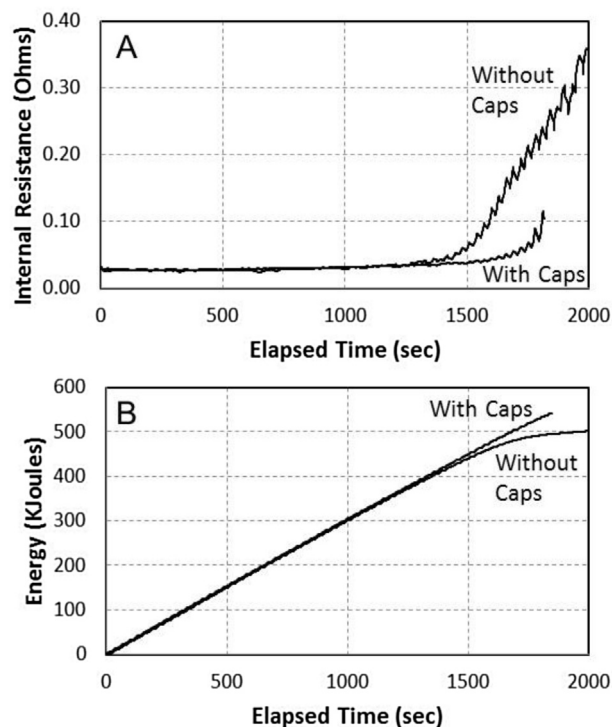


Fig. 3. (A) Internal resistance of the lead acid battery (with and without the capacitor bank) throughout the discharge, (B) Retrieved energy curves for the lead acid battery with and without the capacitor bank.

cannot be predicted by a simple Thevenin equivalent model. It may be argued that this result could simply be a difference in the initial state of charge, and indeed a difference in the initial charge state would give energy curves very similar to these. However, as described in the experimental section, care was taken to insure that the battery was at the same charge state prior to each run. It is likely that there would be a more discernible difference in the curves, the slope in particular, if the load profile had more intense current “spikes.” By way of comparison, the energy loss from charging and discharging the capacitor bank (total internal resistance of about 40 mΩ) was only 1.5 kJ.

The most striking difference in this work was found with the non-rechargeable lithium ion batteries, for which the initial value of R_{int} was estimated to be 270 mΩ. In this case, the total internal resistance of the capacitor bank was about 14 mΩ, much smaller than that of the battery. With a nominal open terminal voltage of 3 V, a steady state current of 2 A, a peak current swing of 2 A, and the estimate of 270 mΩ for R_{int} , the steady state power (with capacitors) is calculated to be 4.92 Watts. Without the capacitor bank, an additional fluctuation loss of 1.08 Watts is expected. Therefore, the capacitors should increase the energy output by 28%.

Fig. 4 gives the power partitioning curves for a portion of the discharge. Again, the power delivery of the capacitor bank is centered about zero, but notice how wide the power swing is compared to that of the battery. The capacitor bank had a much more significant effect than in the previous case. Energy retrieval curves for the two cases, Fig. 5, further illustrates the point. This time note how much steeper the curve is for the system with capacitors than the system without the capacitors. As expected, the slope of the energy retrieval curve was about 30% higher with the capacitors than without the capacitors. Furthermore, note how the system also experiences departure from the ideal linear behavior in the later stages of discharge, near depletion of the battery. The total energy retrieved from the battery was 9.2 kJ when

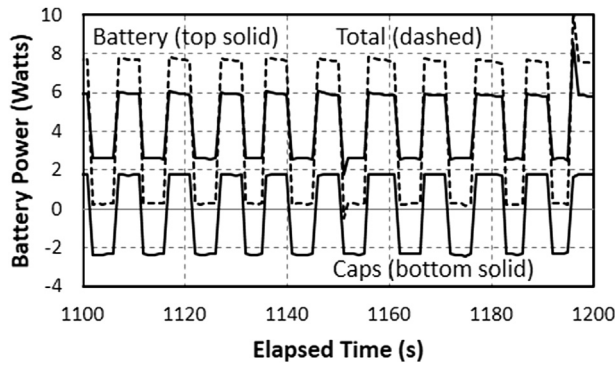


Fig. 4. Power partitioning of the non-rechargeable lithium ion battery/ultracapacitor system during load cycling, showing the contribution from the battery (top solid line) and capacitors (bottom solid line), and the total power (dashed line).

coupled with the capacitors, and 6.3 kJ when discharged alone, an increase of 46% which is well in excess of the expected 28%. This indicates improvement both from the decrease in $I_b^2 R_{int}$ loss (28%, predicted by a simple model), as well as from a longer retention of charge (an additional 18%, not predicted, or even predictable by a simple model). For comparison, the energy loss from repeated charge and discharge of the capacitor bank was found to be about 50 J, quite small compared to the energy retrieved from the battery.

A rechargeable lithium ion battery was evaluated as the final example. The initial value of R_{int} was estimated to be 250 mΩ. Using the simple model, the expected improvement is 19%. In this case, however, there was an additional subtlety in the analysis. Prior to both runs, the battery was charged to the manufacturer's recommended full charge potential of 4.2 V. The capacitor bank was charged to match that potential. However, this is higher than the normal operating voltage of 3.6 V which is quickly attained once load is placed on the battery. Hence, the capacitors were overcharged, which had to be considered in the analysis. Fig. 6 shows how the retrieved energy is partitioned between the battery and the capacitor bank. Unlike the previous two cases, a substantial amount of net energy was obtained from the capacitors, and needed to be removed from the system total for a proper evaluation of the battery performance. (Note: this correction was done for all three batteries studied, but it was negligible in the other two cases.)

Although the main focus is on the battery, it is worth discussing the energy curve for the capacitor bank in a little more detail. An interesting feature is the two regions of increased energy extraction. The first region which levels out at just over 1/2 KJoule occurs because the capacitor bank was overcharged, hence energy

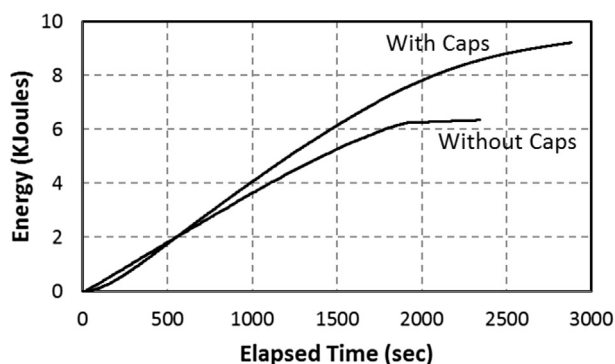


Fig. 5. Retrieved energy curves for the non-rechargeable lithium ion battery with and without the capacitor bank.

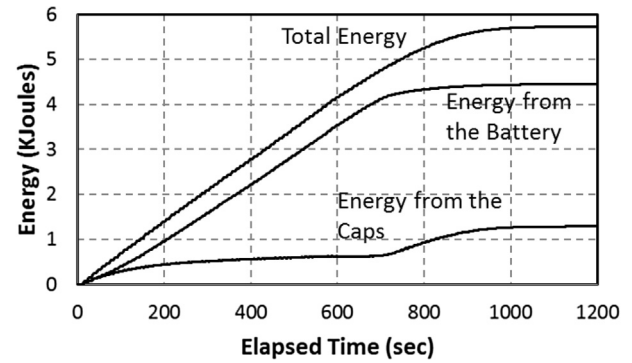


Fig. 6. Energy partitioning in the rechargeable lithium ion battery/ultracapacitor system, showing the total energy, the energy retrieved solely from the battery, and the energy retrieved solely from the capacitors.

was obtained from the capacitors as well as from the battery. The second region which starts 700 s into the run and levels out at nearly 1.5 kJ occurs because the battery has been depleted of charge and nearly all of the energy of the system is from the capacitors. Furthermore, note that the energy curve for the battery levels out quickly after 700 s; the battery charge has been depleted. None of the energy obtained from the capacitor bank is of interest with regard to evaluating battery performance, hence was discounted by determining the energy obtained from the battery current alone.

Fig. 7 shows the with/without capacitor comparison for the battery energy alone. The slope of the “with capacitor” energy curve is about 8% higher than that of the “without capacitor” curve, considerably less than the expected value of 19%. However, the total retrievable energy increased from just over 3 kJ to about 4.5 kJ, an improvement of 40%. (Note: from subsequent evaluations not reported here, we believe that the capacitors were starting to degrade, which would account for the difference in slopes of the expected versus experimental energy retrieval curves.) As with the non-rechargeable lithium ion battery system, the improvement afforded by the capacitors was evident both from less $I_b^2 R_{int}$ loss (linear portion of the curve), and in the retention of charge (leveling portion of the curve). Again, the calculated energy loss from charging and discharging the capacitor bank (30 J) was small compared to the energy retrieved from the battery.

5. Summary and conclusions

Three battery/capacitor systems have been evaluated in order to quantify the improvement of battery performance afforded by the

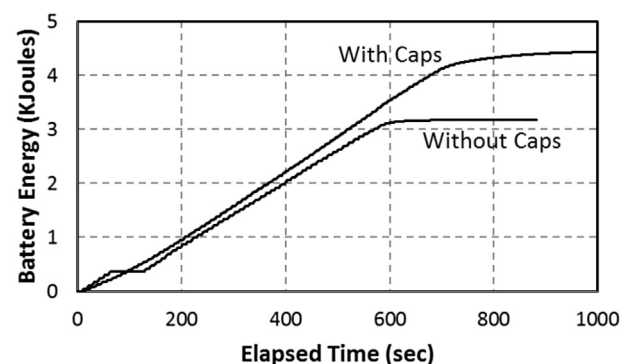


Fig. 7. Retrieved energy curves for the rechargeable lithium ion battery with and without the capacitor bank.

capacitor bank. In all systems, the capacitors increase the amount of usable energy that could be retrieved from the battery. This was attributed not only to the decrease in power loss internal to the battery, but also to an increase in the amount of charge that could be retained, presumably through more efficient electrode chemistry. Because of the low internal resistance of the lead acid battery, the improvement in energy retrieval by the capacitors was due almost solely to charge retention. The improvement by removing current fluctuation loss was negligible. On the other hand, lithium ion batteries, with a much higher internal resistance, showed improvement, both by removal of the current fluctuation loss, and by retention of charge.

The improvement realized was on the order of 8% for a lead acid battery, 46% for a non-rechargeable lithium ion battery, and 40% for a rechargeable lithium ion battery. Such extension of the charge life is expected to translate to improved life time of the power system, as reported by Hochgraf et al. [10].

Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jpowsour.2014.06.086>.

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